ARKIV FÖR FYSIK Band 17 nr 10

Communicated 11 November 1959 by M. Siegbahn

The high-frequency deflection method for measuring short half-lives

Part 1. Principle and some measurements

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With 10 figures in the text

ABSTRACT

Some investigations of the high-frequency deflection method for measuring short half-lives have been made. The method has shown to be useful for measuring the half-lives of moderately converted γ-transitions below 1 MeV fed by converted γ-transitions, β-radiation or possibly also α-radiation. Half-lives in the range 10^{-10} s–10^{-13} s should be measurable from the slope of the resolution curve. With a frequency of 146 Mc/s, a resolving time of $3 \cdot 10^{-10}$ s has been obtained for the test arrangement for 300 keV conversion electrons. The slope of the resolution curve corresponds to a half-life of $3 \cdot 10^{-11}$ s.

Some preliminary measurements with the following results have been performed.

For the 279 keV level in Tl^{203}: $T_{1/2} = (2.2 \pm 0.3) \cdot 10^{-10}$ s

For the 313 keV level in U^{233}: $T_{1/2} = (2.0 \pm 0.3) \cdot 10^{-10}$ s

For the 2385 keV level in Pb^{206}: $T_{1/2} \leqslant 3 \cdot 10^{-11}$ s

For the 239 keV level in Bi^{212}: $T_{1/2} \leqslant 8 \cdot 10^{-11}$ s.

1. Introduction

The problem of measuring very short life times (less than 10^{-10} s) of isomeric states in nuclei has been attacked in several ways. Nuclear resonance–fluorescence and coulomb excitation are examples of such methods. Their usefulness is, however, often limited and it has not been possible to use them as a general method for investigation of transition rates. The lack of such a general method is very unsatisfactory since most of the known states of nuclei decay faster than 10^{-10} s and a determination of the life times of these states is often a sensitive test of, for example, different nuclear models.

For half-lives longer than about 10^{-10} s, a relatively general method exists, namely the delayed coincidence method. During the past years some new methods for the range $< 10^{-10}$ s have been proposed (1), (2), (3). In the work described in this paper, some investigations of the method (3), using high-frequency deflection of charged particles, are carried out. This method involves the usual coincidence technique, but, instead of measuring possibly occurring delays after the detection of the radiation, the time-determination is performed on the radiation itself. This has the advantage that the time-spread in the detection of the radiation is avoided. The method is useful for converted γ-transitions fed by converted γ-transitions, β-radiation or possibly also α-particles. Since high energy-resolution can be used, and since the direction of the deflection can be chosen so that no energy mixing occurs, isotopes with very complicated decay schemes can be investigated. A description of the test arrangement and some preliminary measuring results are given in the following.

2. Method

Fig. 1 A shows a diagram of the principle.

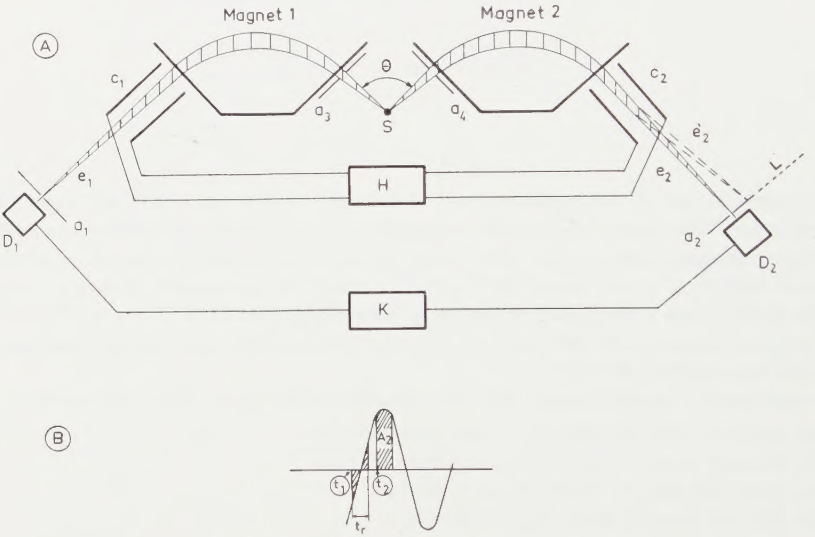

Fig. 1. A. Simplified diagram of the principle. The symbols used have the following meaning:

$a_{1,2,3,4}$ = Apertures
$C_{1,2}$ = Deflection condensers
$D_{1,2}$ = Detectors
$e_{1,2}$ = Electron trajectories
H = High-frequency source
K = Coincidence unit
S = Radioactive source

B. Time-positions for the electrons in the deflection moment. t_r = Transit time for the electrons through the deflection condensers.

Suppose that the source S emits two conversion electrons in cascade. The magnet I is set to focus the first one and the magnet II to focus the second one on the detectors D_1 and D_2 respectively. The coincidence unit K registers coincident electron-pairs. So far it is an ordinary electron-electron coincidence arrangement. If now the plane parallel condensers, C_1 and C_2, are connected to a high-frequency source, the spectrometer lines are swept backwards and forwards over the apertures a_1 and a_2 respectively. If the electron e_1 passes through the condenser C_1 at the time t_1 (fig. 1 B), it will undergo no deflection. If e_2 is an electron in prompt coincidence with e_1 it will also pass through without deflection provided that the phase-difference between

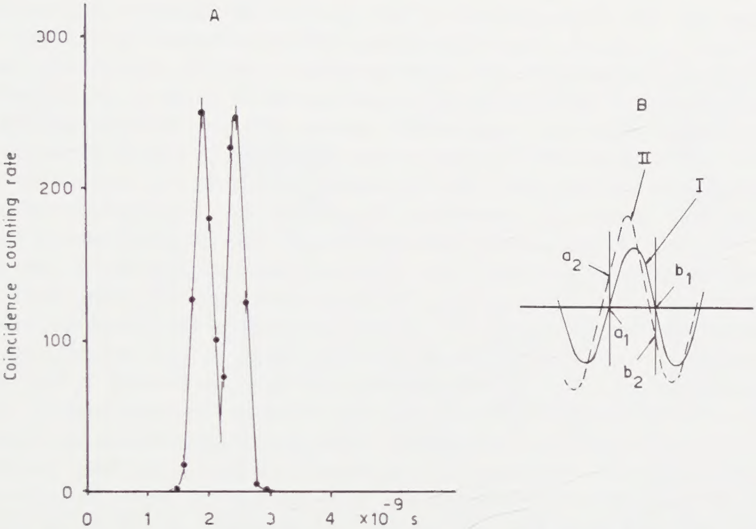

Fig. 2. A. Time-resolution curve for a Bi^{206} source, obtained by varing the D.C.-voltage on one of the deflection condensers. The K-conversion electrons from the cascade 398 keV–184 keV were focused by the magnets. B. The phase-positions of the voltages on the two deflection condensers. The two possibilities for the positions of the two coincidence-curves are indicated by a_1–a_2 respectively b_1–b_2.

the voltages on C_1 and C_2 corresponds to the differences in transit times for the two electrons through the magnets. If e_2 ($\grave{e}_2$) had been emitted a short time after e_1, then it would have received a deflection proportional to the shaded area A_2 indicated in fig. 1B.

Thus, for emission-time differences exceeding a certain value, the electrons e_2 will fall outside the aperture a_2, (provided that the electrons e_1 have been detected). By measuring the number of coincidences as a function of the position of the aperture a_2 along the line L, a time resolution curve will be obtained. (It is assumed in this discussion that the sweep amplitude is large enough to sweep the spectrometer line considerably beyond the apertures.) Fig. 2A shows a typical experimental time-resolution curve measured with a Bi^{206} source. The magnets were set to focus the 96 keV k-conversion electrons from the 184 keV transition and the 310 keV k-conversion electrons from the 398 keV transition. In this case the spectrometer-line is displaced instead of moving the aperture as this is easily done by varying a D.C. voltage on one of the deflection condensers. The time-resolution curve has two peaks, the distance between which depends on the phase-difference between the high-frequency voltages on the deflection condensers. The two peaks are due to the fact that the electrons can be deflected in two directions depending on the polarity of the high-frequency voltage in the deflection moment. Fig. 2B shows the two possibilities, indicated by $a_1 - a_2$ and $b_1 - b_2$.

If the phase-difference is equal to the difference in transit time for the electrons through the magnets, the two peaks will coincide and one symmetric curve will be obtained. This position is not convenient to use because a delay in the emission of the second transition of the cascade will give a symmetrical broadening of the resolution curve since the asymmetry of the two curves appears in opposite direction. This is seen from fig. 2B. If the position of the aperture in channel I corresponds to the phase-positions a_1 and b_1, then coincidences will be obtained for aperture-positions in channel II corresponding to the phase positions a_2 and b_2 respectively. In the case of delayed emission, if this should appear in channel II, both a_2 and b_2 shift towards larger amplitude. Thus two asymmetric curves will be obtained having reversed asymmetry. If the phase-shift is equal to the difference in transit times for the electrons through the two magnets, the two curves will form one symmetric curve. If, instead, the two peaks are completely separated, two asymmetric curves will be obtained. The slope of one side of these curves will then be a measure of the half-life of the level in question, provided that a clear asymmetry appears. If the amplitude of the sweep voltage is large enough, the range near zero deflection will be approximately linear with respect to the time. Thus, variation of the position of the aperture can be compared to the variation of the time-delay in the conventional delayed coincidence technique. The curves obtained can thus be treated in the same way.

In order to determine the time-scale one has to know the time-interval to which a displacement of the aperture corresponds. This can be determined by introducing a known phase-difference between the condenser voltages and then measuring the change in distance between the two peaks of the resolution curve. Because of the low coincidence counting-rate, this will not be very accurate. A better way is to do as follows. By assuming the spectrometer line to have a triangular shape (which is a very good approximation, see fig. 3B), the intensity distribution at the aperture during the sweep can be calculated. (These calculations, together with the description of some electronic equipment will be published later in a separate paper (4).)

The following expression is a very good approximation for the intensity distribution:

$$(1)\quad \begin{aligned} I(X,A) = \frac{I(0,0)}{\pi}\Bigg[& (A\,X-1)\left(\arcsin\left(\mathrm{X}-\frac{1}{A}\right)-\arcsin X\right)+ \\ & + A\left(\operatorname{cosarcsin}\left(X-\frac{1}{A}\right)-\operatorname{cosarcsin} X\right)- \\ & -(A\,X+1)\left(\arcsin X-\arcsin\left(X+\frac{1}{A}\right)\right)- \\ & -A\left(\operatorname{cosarcsin} X-\operatorname{cosarcsin}\left(X+\frac{1}{A}\right)\right)\Bigg]; \end{aligned}$$

With the restriction: for $z \geqslant 1$, arcsin z must be put equal to $\left(\frac{\pi}{2}\right)$.

The symbols used have the following meaning:

$A = (K/\Gamma)$
$X = (a/K)$
K = Sweep amplitude (= displacement of the spectrometer line at the aperture).
Γ = Width at half-maximum of the spectrometer line, measured with the aperture used.
a = Position of the aperture.
$I(0{,}0)$ = Peak intensity of the spectrometer line.

Fig. 3 A shows the function (1) for different values of the parameter A.

When A increases, the two maxima come closer to $X = 1$ corresponding to the maximum amplitude of the sweep. The maximum intensity will not appear at maximum amplitude because at this point only one half of the line is swept over the

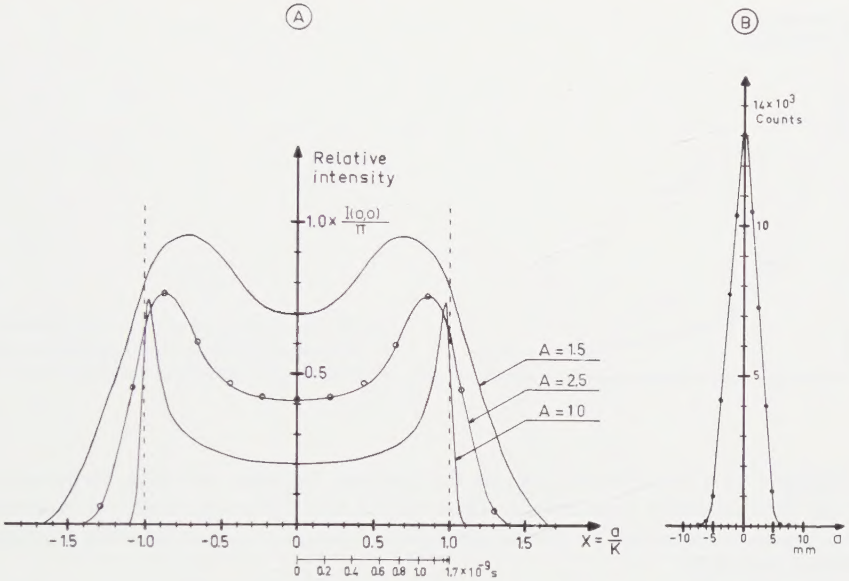

Fig. 3. A. The function (1) for three different values of the parameter A. The open rings in the intermediate curve are experimental points for a sweep amplitude corresponding to $A = 2.5$. B. The shape of the spectrometer lines.

aperture. In order to obtain the time-calibration, the value of A has to be determined. This can be carried out by measuring the intensity at $X = 0$ for different sweep amplitudes. For $X = 0$ equation (1) reduces to:

$$I(0, A) = \frac{2\,I(0,0)}{\pi}\left(\frac{\pi}{2} - A\right) \quad \text{for } 0 \leqslant A \leqslant 1 \tag{2}$$

$$I(0, A) = \frac{2\,I(0,0)}{\pi}\left(\arcsin\left(\frac{1}{A}\right) + \sqrt{A^2 - 1} - A\right) \text{ for } A \geqslant 1$$

The first expression corresponds to the case when the line is not swept outside the aperture.

Fig. 4 shows the ratio $\dfrac{I(0,0)}{I(0,A)}$ for different A-values.

This ratio corresponds to the ratio between the intensities with and without the sweep connected.

The open rings in fig. 4 are experimental points measured by varying the amplitude of the sweep voltage. The same straight line for small sweep voltages appeared in the experimental curve as well as in the theoretical one. When fitting this straight line to the theoretical curve, the other points followed the theoretical function. The parameter A can thus be determined by measuring the ratio between the intensity with and without the sweep connected. The middle curve in fig. 3 A is drawn for $A = 2.5$. The open rings illustrate the experimental intensity distribution for a sweep amplitude which gives an intensity ratio corresponding to this A-value.

Another way to obtain a time-resolution curve is to measure the coincidence

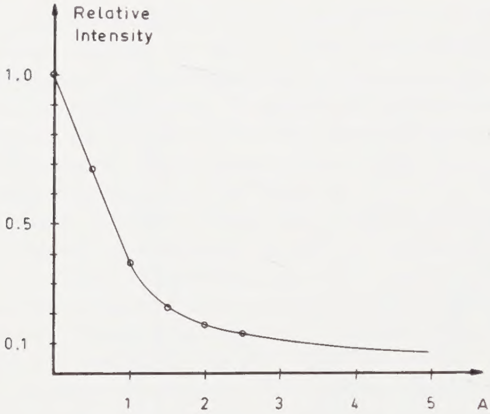

Fig. 4. The intensity at × = 0 as a function of *A*. The solid curve is the theoretical function while the open rings are experimental values.

counting-rate as a function of the phase-difference between the high-frequency voltages on the deflection condensers. This way is more like the delayed coincidence method because changing the phase-difference is the same as introducing a delay into one of the channels.

Fig. 5 shows a typical curve for this method of measurement. In this case a Pa^{233} source was used. One magnet was set to focus 58 keV β-radiation and the other to focus the conversion electrons from the 313 keV-level. It appears that the peak will be repeated each half-period of the cycle. In the case of delayed transitions, the curves will be asymmetric with a slope corresponding to the half-life in question.

The method described first for obtaining a time-resolution curve is most convenient in connection with a multi-detector system by means of which the whole resolution curve can be measured at the same time. Such a multi-detector system will be introduced in a further development of the arrangement. As mentioned above, the two curves (corresponding to the two deflection directions), have to be separated in order that an asymmetry caused by a delayed transition should be visible. Thus, the coincidence counting-rate will be one half of the optimum value corresponding to zero phase-difference. The optimum counting-rate will, however, be obtained if the resolution curve is measured by changing the phase-difference, which makes this method most suitable for single-channel measurements.

The resolving time obtainable with the high-frequency deflection method depends on the measured width of the spectrometer line and the amplitude and the frequency of the high-frequency source. By increasing the amplitude, the resolving time is improved, but the coincidence counting rate is decreased. The most convenient way to improve the time-resolution is to increase the frequency as this will not change any intensity figures. With a frequency of 146 Mc/s, a resolving time of 10^{-10} s is reasonable. The frequency limit for using usual resonance-circuits (Lecher-circuits) is about 1000 Mc/s with which a resolving time of about 10^{-11} s is possible. By the use of wave-guides, still higher frequencies can be used. The limit for the resolving time can be estimated to be about 10^{-12} s. This limit is mainly set by the size of the source and aberrations in the deflection system. Because half-lives of about one tenth of the resolving time can be obtained from the slope of the resolution curve, the limit for the half-life measurements will be about 10^{-13} s. In some cases comparison methods can be used, decreasing the limit in these cases to about 10^{-14} s.

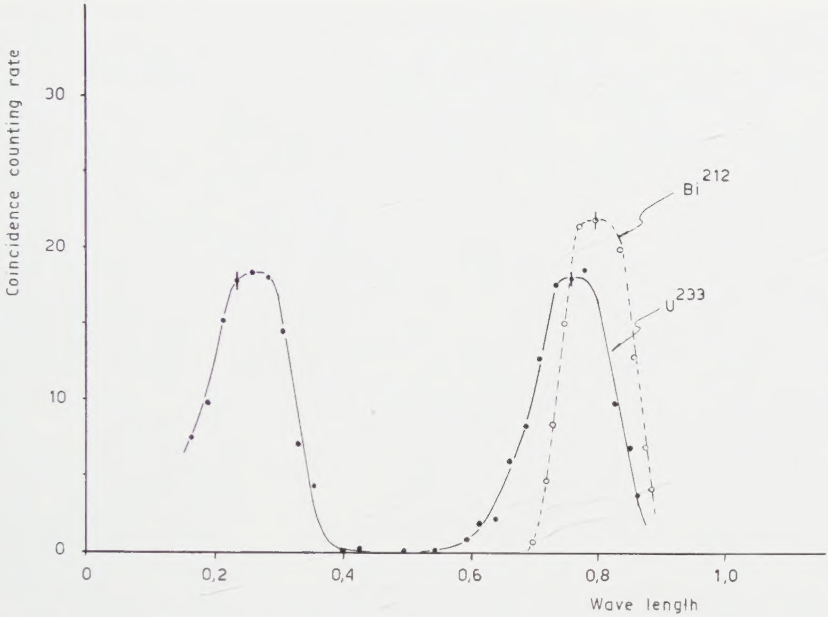

Fig. 5. Time-resolution curve obtained by varying the phase-difference between the high-frequency voltages on the deflection condensers. The distance between the curves corresponds to one half of the high-frequency period. The curve was measured with a Pa^{233} source with one channel accepting 58 keV β-radiation and the other K-conversion electrons from the 313 keV transition. The curves to the right are plotted on a logarithmic scale in fig. 10.

In the arrangement illustrated in fig. 1, where the focusing takes place before the deflection, the limit for the resolving time is determined also by the time-spread due to different transit-times for the electrons through the magnets. With small magnets, however, this time-spread can be held rather low, totally about 10^{-10} s for the test arrangement for electron-energies of about 100 keV. With larger magnets, where there is more room on the source-side, it is more convenient to place the deflection plates in front of the magnets.

The good resolution of the magnets used and the direction of the deflection makes the method useful also for isotopes with very complicated decay-schemes. The method can also be used for isotopes decaying with continuous β-radiation. Some experimental examples are given in the last part of the paper. An advantage is also that there will always be a distinct line in the deflection direction, with only the detector background present apart from the line, independent of the shape of the energy spectrum focused.

Due to the low transmission of the magnets used, rather strong sources are necessary. The limit for the source strength is set by the resolving time obtainable. For $2\tau = 0.1$ mμs the source must not be stronger than 3 mC, if the real to chance coincidence ratio is to be about 100. The coincidence counting rate at 0.1 % transmission, with the sweep connected, will, for example, be about 6 per minute for two 500 keV $M1$ transitions in cascade for $Z = 82$. For 200 keV $M1$ transitions the situation is about 100 times more favourable.

3. Experimental set up

Fig. 6 shows a block-diagram of the arrangement.

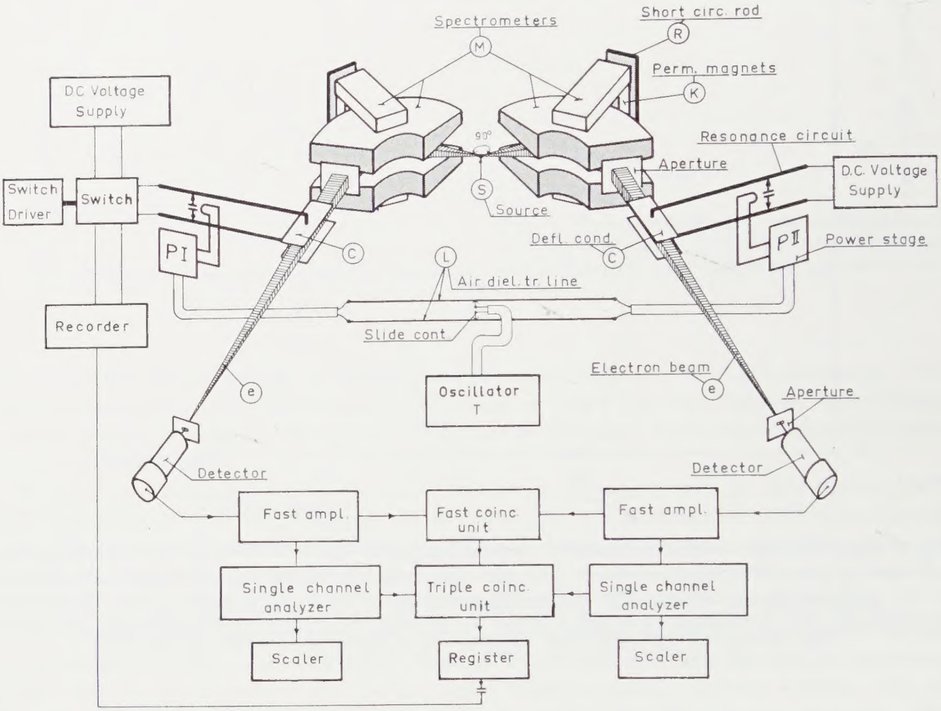

Fig. 6. Block-diagram of the experimental set up.

Because the magnets are double focusing, the deflection is carried out in the direction perpendicular to the radial focusing plane. In this way, mixing of spectrometer lines during sweep is avoided. The magnets have a transmission of between 0.1 and 0.2 per cent and the line width at half-maximum is at best 5 mm for a 1 mm^2 source, corresponding to a resolution of about 0.3 %. An electrostatic system between the source and the magnets increases the transmission with a factor of two or even more, depending on the electron energy. (These arrangements will be described later in a separate paper (5).) In order to attain the required stability of the field permanent magnets are used. The field is varied by a short-circuiting iron rod. The magnets are seen to the left in Fig. 7, which shows a photograph of the arrangement.

The mean radius of the electron paths is about 15 cm. The magnets are oriented in such a way that the angle between the incident electron beams is about 90°. The reason for this is that the electrons should not pass through any material. The source to magnet distance is about 5 cm, giving an image to magnet distance of 120 cm. This long distance is very convenient for the deflection because a rather low high-frequency amplitude is required. The deflection of the electrons depends also on the length of the condenser-plates and the distance between them. The smallest plate-separation, 3 cm in the actual case, is determined by the diameter of the outgoing

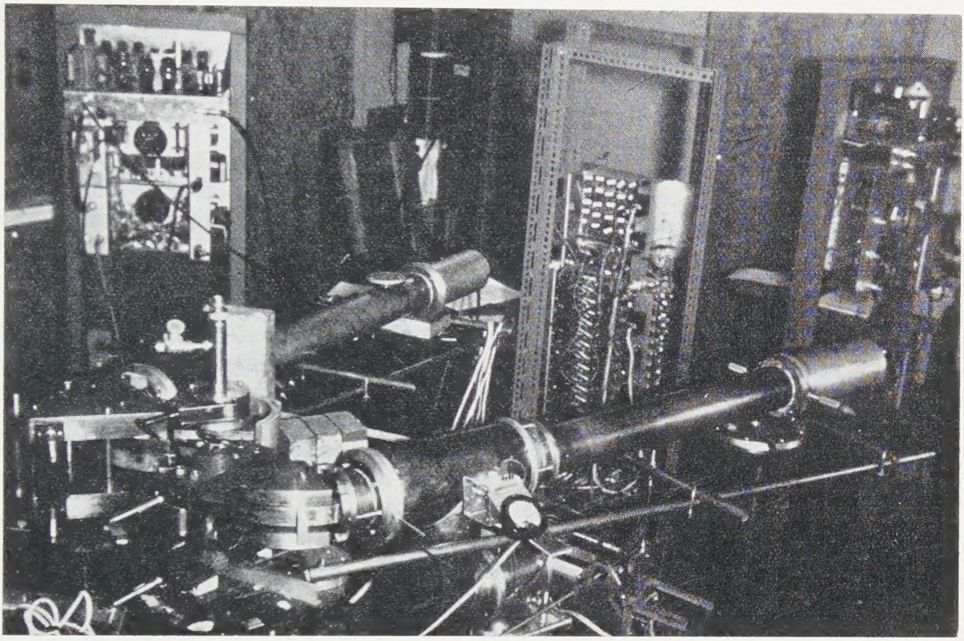

Fig. 7. Photograph of the test-arrangement. The magnets are seen to the left. The large tubes near the magnets contain the deflection system.

beam of the magnet. The length of the plates is determined by the transit times of the electrons through the condensers with respect to the frequency used. For 146 mc/s, a length of 15 cm is convenient. The amplitude required to obtain a suitable deflection for, for example, 300 keV electrons is about 3 kV. The deflection condenser is mounted in the end of a short-circuited transmission-line. For such a line with a load capacitor (c), the resonance length (l) is less than a quarter of a wave-length (λ). The resonance condition is: $\operatorname{tg} 2\pi l/\lambda = 1/\omega c z_0$, where z_0 is the characteristic impedance of the line. This condition is another limit for the size of the condenser, especially for higher frequencies. The high-frequency voltage is generated in the oscillator T and fed via the transmission line L to the power stages PI and PII. The input slide connector of the line L can be moved along the line. The anode-circuit of the power stages are then coupled inductively to the deflection circuits. The power required to obtain condenser voltages of, for example, 3 kV is about 25 watts. In order to avoid high-frequency discharges in the condensers, a D.C. voltage is connected to the plates. As a maximum 600 volts were needed in the measurements made. In the anode-voltage supply, a relay circuit is introduced to turn off the anode voltage if the anode-current exceeds a certain value, which often happens at the start of a measurement due to discharges. After some minutes it is automatically turned on again. The waiting time is determined by the speed with which the vacuum-pump pumps out the gas created during discharges.

The detectors used are plastic scintillators mounted on 6342 photomultipliers. The detector pulses are fed to a fast coincidence-circuit with a resolving time of $2\tau = 3.5$ mμs. (At energies below 60 keV $2\tau = 7$ mμs was used.) This figure corresponds to one half of the high-frequency period. A shorter resolving time is not required because the final resolution is determined by the sweep conditions, provided that the coincidence unit has a resolving time that is less than or equal to one half of the high-frequency cycle.

When the measurements are carried out by sweeping the D.C. voltage on one of the deflection condensers, this step regulation is made automatically by a switch-driver. The step-voltage is then measured with a recorder. In order to obtain the coincidence data on the same recording paper, a wide pulse from the coincidence circuits is fed directly to the recorder through a condenser to give a narrow spike on the paper.

The next step in the development of the arrangement is to increase the frequency and improve the statistics by introducing a multi-detector system. This system will consist of 15 plastic scintillator-strips mounted on small light-guides connected to five photomultipliers. One of these photomultipliers is connected to all scintillators in order to give fast pulses to the fast coincidence-unit. The other four photomultipliers are connected to four scintillators each. The pulses from these four multipliers are fed into a slow coincidence-system by means of which the channel in which an electron has been detected can be determined.

Measurements

1. By sweeping the D. C. voltage on one of the condensers

In order to test the method, some measurements were made with a Bi^{206} source. This isotope decays with a half-life of 6.4 days to Pb^{206} (8). The sources were made in the synchrocyclotron in Uppsala by bombarding lead targets with protons. Carrier-free chemical separations of the bismuth were then performed and the activity was electroplated onto copper-foils. The active area was about 2×1 mm^2. The measurements were carried out with one magnet set to focus the 96 keV K-conversion electrons from the 184 keV transition and the other magnet to focus the 310 keV K-conversion electrons from the 398 keV transition. The position of the transitions can be seen in the level scheme given in fig. 8. The phase-difference between the high-frequency voltages on the deflection plates was adjusted so that two well separated curves were obtained.

The amplitude of the high-frequency voltage was intended to be increased until the optimum resolving time, about 0.1 mμs, was obtained. This figure is determined partly by the time-spread due to different transit times for the electrons through the magnets and partly by the convenient high-frequency amplitude with respect to the coincidence counting-rate. Because of heating effects in the deflection-system at large high-frequency amplitudes, discharges occurred which limited the resolving time obtainable to 0.35 mμs. This figure corresponds to a sweep-parameter value of $A = 4$. The measurements will be repeated with higher sweep-frequency and with a water-cooled deflection system. The shape of the deflection-plates will be chosen so that the time-spread due to different path-lengths will be corrected for. From the A-value obtained, the time-calbriation could be determined from equation (1).

Fig. 8 shows the time-resolution curve obtained plotted on a logarithmic scale. (Fig. 2 shows the same curve on a linear scale.) The width at half-maximum of the two curves corresponds to a resolving time of $2\tau = 3.5 \cdot 10^{-10}$ s. The slope of the curves corresponds to a half-life of $3 \cdot 10^{-11}$ s, which can be set as the upper limit for the half-life of the 184 keV transition. The ratio between real and chance coincidences

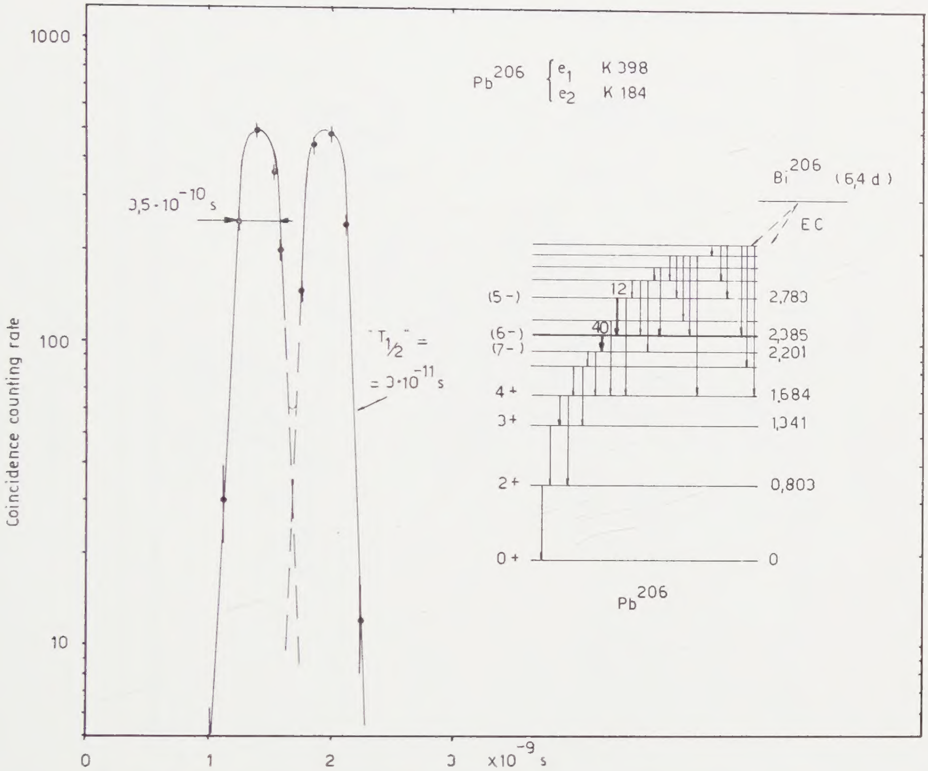

Fig. 8. To the left is seen the time-resolution curve for the 189 keV transition in Pb^{206} measured with the D.C. sweep-voltage and with the high-frequency voltage connected. The amplitude of the high-frequency voltage used corresponds to an A-value of 4. The number of chance coincidences was in this case negligible. To the right is seen the decay scheme of Bi^{206} (6). Some of the energy and spin values are indicated. The measured cascade is indicated with heavy lines. The numbers at the head of these transitions are intensity figures in per cent per desintegration.

was about 500, implying that the number of chance coincidences is negligible. According to W. True and K. Ford (7) this level should have a half-life of about $1.5 \cdot 10^{-11}$ s as determined from shell model calculations. Because no suitable prompt transition was available, this figure could not be checked more accurately. The total measuring time for the curve shown was about 3 weeks.

2. *By shifting the phase*

a. The 279 keV level in Tl^{203}

The half-life of the 279 keV l-forbidden $M1$ transition in Tl^{203} has been measured several times (8). The mean value of these measurements is $2.5 \cdot 10^{-10}$ s, which is a suitable value in order to test the method described above with a known half-life.

The 279 keV transition in Tl^{203} is present in two types of decay, namely in the β-decay of Hg^{203} and in the EC-decay of Pb^{203}. In the measurements described here the latter type of decay was chosen because a carrier-free sample could be obtained by a simple method. The sources were produced by bombarding Tl with protons in

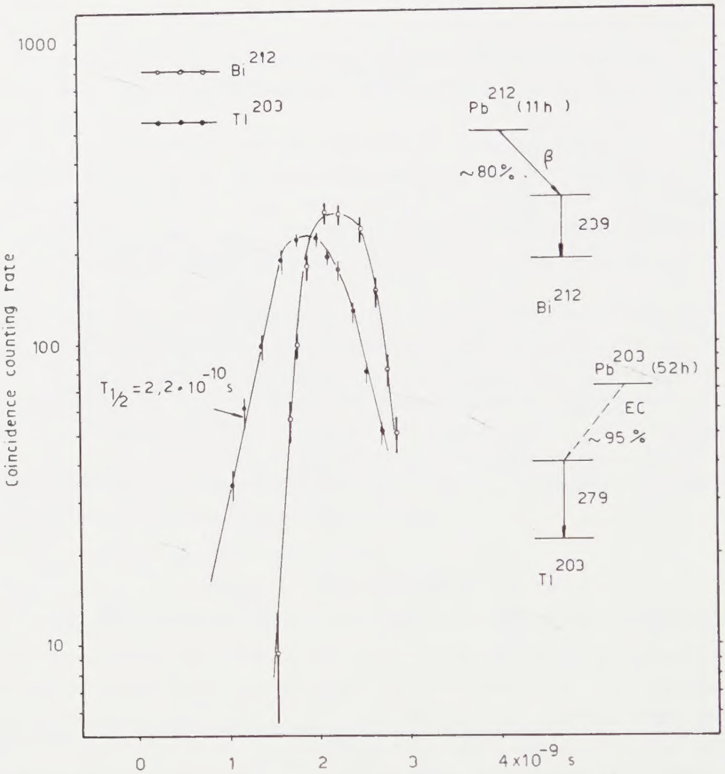

Fig. 9. Time-resolution curve for the 279 keV level of Tl^{203} measured by phase-shift. To the right is seen the level scheme of Pb^{203} and Pb^{212}. One magnet was set to focus 58 keV Auger-electrons preceding the delayed 279 keV transition in Tl^{203} or 58 keV β-radiation preceding the prompt 239 keV transition in Bi^{212}. The other magnet was set to focus the K-conversion electrons from the 279 keV transition in Tl^{203} and the 239 keV transition in Bi^{212} respectively.

the synchrocyclotron in Uppsala. After a chemical separation, the sources were prepared by evaporating Pb^{203} onto a copper-foil.

The measurements were carried out by measuring coincidences between 58 keV Auger-electrons and K-conversion electrons from the 279 keV transition. Because the Auger-spectrum is composed of many close-lying lines with about the same intensities, it was convenient to allow more than one line to be detected in order to increase the coincidence counting-rate. By means of an sector magnet just in front of the detector, it was possible to focus more than one line onto an area suitable for the size of the detector. This magnet also decreased the background caused by scattered electrons.

Fig. 9 shows the time-resolution curve obtained by shifting the phase. From the slope of the curve the half-life of the 279 keV level in Tl^{203} can be determined to be $(2.2 \pm 0.3) \cdot 10^{-10}$ s. The same value is obtained it the centroid shift is measured. Because Auger-electrons of the same energies also appear to the same amount in the conversion of the 279 keV transition, 50 per cent prompt coincidences were subtracted. The ratio between real and chance coincidences was about 100, implying that a very small number of chance coincidences appeared. The curve

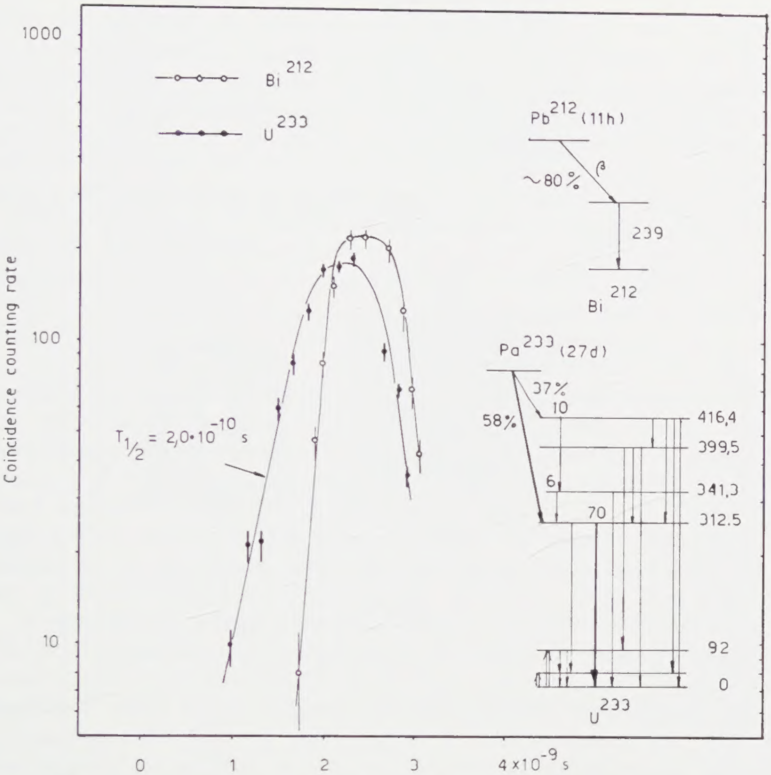

Fig. 10. Time-resolution curve for the 313 keV level of U^{233} measured by phase-shift. In this case also a Pb^{212} source was used for measuring the prompt coincidence curve. One channel was set to accept 58 keV β-radiation while the other was set to accept K-conversion electrons from the 239 keV transition in Pb^{212} and the 313 keV transition in U^{233} respectively.

shown is a sum of four different measurements each taking one week to perform. Taking into account intensity effects, the amplitude of the high-frequency sweep-voltage was increased just so much as was required to obtain a clearly asymmetric curve. With this amplitude, a resolving time of 0.8 mμs was obtained for the prompt coincidence resolution curve. As prompt transition, the 239 keV transition in Bi^{212} in coincidence with 58 keV β-radiation was used. The prompt coincidence resolution curve has a slope corresponding to a half-life of $8 \cdot 10^{-11}$ s. This value can be set as an upper limit for the half-life of the 239 keV level. The position of the prompt coincidence curve in fig. 9 is corrected for the difference in energy between the prompt and the delayed transition. The source strength of the Bi^{212} source was a few hundred μC giving a coincidence counting-rate of about 7 per minute at the start without the sweep connected. The curve shown is a sum of 10 different measurements.

b. The 313 keV level in U^{233}

Pa^{233} decays to U^{233} mainly by two β-groups with maximum energies of 150 keV (37 %) and 257 keV (58 %) (8). The latter group feeds the 313 keV level, which decays to the ground state by a very intense $M1$ transition.

The Pa^{233} source was obtained from a (n,γ) reaction on Th^{232} in the Swedish reactor RI. In this reaction, the Th^{233} produced decays by β-radiation to Pa^{233}. The protoactinum activity was chemically separated from the thorium and electroplated onto a thin platinum foil. The area of the source was about 1×2 mm^2.

The 313 keV level in U^{233} was first intended to be used as prompt transition in the measurements of the half-life of the 279 keV level in Tl^{203}. The 313 keV level should be suitable for this purpose because the K-conversion electrons from this transition have about the same energy as the K-conversion electrons from the 279 keV level in Tl^{203} and the energy at maximum intensity for the β-radiation feeding the 313 keV level is very near to 58 keV. Thus, the same setting could be used in the β-channel and only a small adjustment was required in the other channel. The result of this "prompt curve" measurement was, however, an asymmetric curve with a slope and a centroid shift corresponding to a half-life of $(2.0 \pm 0.3) \cdot 10^{-10}$ s.

Fig. 10 shows the time-resolution curve obtained for the 313 keV-level measured by phase-shift. The prompt coincidence resolution curve is the same as in fig. 9. Its position is corrected for the difference in energy between the prompt and delayed transition. It is not excluded that some of the coincidences were due to the cascade 75.1 keV–28.8 keV–313 keV, because some of the L_1-conversion electrons from the 75.1 keV ($E_{e^-} = 54$ keV) transition could have been detected in the wide β-channel. Also some of the β's in the 150 keV group were detected. Thus, some of the transitions preceding the 313 keV level, especially the 28.8 keV transition, could be due to the half-life measured. However, from available intensity figures, the cascade $\beta^- - 313$ keV can be estimated to cause at least 80 % of the coincidences obtained. The half-life obtained, $(2.0 \pm 0.3)\ 10^{-10}$ s, is thus probably due to the 313 keV level. The uncertainty is caused by the arrangement with the detector magnet which made it difficult to change the energy and to determine the energy-range covered. This system is now in course of being reconstructed in order to be able to make more certain energy-range determinations. The strength of the Pa^{233} source was a few hundred μC, giving a real to chance coincidence ratio of about 100. The total time required to measure the curve shown was two weeks.

ACKNOWLEDGEMENT

The authors are much indebted to Dr. B. Åström and Dr. K. G. Malmfors for their interest in this work. For chemical separations we want to thank Ing. O. Melin. We are also grateful to the cyclotron crew in Uppsala for providing several irradiations. Finally we thank Miss G. Oelsner, B.Sc., for correcting the English, and Messrs. S. Berglund and R. Selén for skilful technical assistance.

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Tryckt den 15 mars 1960

Uppsala 1960. Almqvist & Wiksells Boktryckeri AB